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Sea Surface Temperature monitoring in Italian Seas: Analysis of long-term trends and short-term dynamics

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ABSTRACT

The aim of this paper is to give an overview of the various measurement collections that contribute to the observation of Sea Surface Temperature in Italian Seas. Long term time series are collected since the 19th century but are affected by a large systematic errors. Despite the lack of accuracy, their contribution to the analysis of trends is fundamental into the climate change context. On the other hand, recent systematic observations are more accurate and continuous in space and time. Short term time series better define the status of the temperature during the last years in term of variability and dynamics.

1. Introduction

Sea Surface Temperature (SST) is one of the most important physical parameter in marine climatological studies. It is a relevant predictor of a number of meteorological variables, such as parameters of general circulation and windstorm formation, it is fundamental in climate modelling, for studying earth heat balance, and to detect atmospheric and oceanic circulation patterns and anomalies, moreover it is critical in the evaluation of the biological component.

Quality of long time series is variable, several different methods of measuring have been used over the years through different instruments including ships, buoys, coastal platforms, or oceanographic tools. Datasets are often limited in space and time, especially at the beginning of the twentieth century and during the world wars. In the last decades, quality of in situ and remote sensed data has improved significantly in parallel with the increase of marine observations and a large number of studies have been implemented in order to investigate the long term SST changes and the effects of spatial variability over the marine system.

SST datasets have been independently developed by research groups with different upgrading time-frame. Some studies use only in situ observations, as in the case of the Extended Reconstructed SST (ERSST, [1,2]) and the Hadley Centre SST, version 3 (HadSST3, [3,4]). In others cases both in situ and satellite observations are used, as for the National Centers for Environmental Prediction (NCEP) Weekly Optimum Interpolation SST (WOISST, [5]) and the National Centers for Environmental Information (NCEI) Daily Optimum Interpolation SST (DOISST, [6]).

In situ observations are available from 1600 but methods of measurement and locations have changed substantively through time. It is fundamental to reconstruct the measurements history with respect to adopted observing protocol and possible systematic bias sources. These issues have driven several studies to highlight the importance of uncertainty in SST measurements and to adjust and homogenise these time series, such as in [7].

The global-scale features and long-term trends study using different SST products show a general agreement (e.g., [8,9]); the differences among the available products mostly result on how the in situ SST data biases are corrected [2,7], in particular main result from quality control and gap-filling procedures, especially in early record periods. In the present work the use of the “Rete mareografica nazionale” (Italian tide gauge monitoring network – RMN) SST data could represent a challenge in order to add knowledge and information useful to quantify the uncertainty which led to potential innovations and improvements on SST monitoring.

2. Data sets

Four dataset have been analysed in this study as represented in Fig. 1.

1. Long term time series are extracted from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS; [10]). It represents the most complete and heterogeneous collection of surface marine data, based on records from a great number of sources such as ships, buoys and other platform types as summarised in Fig. 2. The first systematic observations were collected using buckets made

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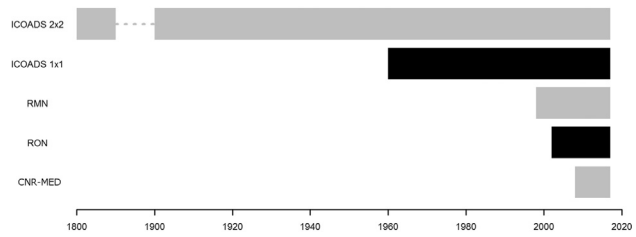

Fig. 1. SST Dataset from 1800. ICOADS dataset has been splitted in two subset according to the different spatial resolution.

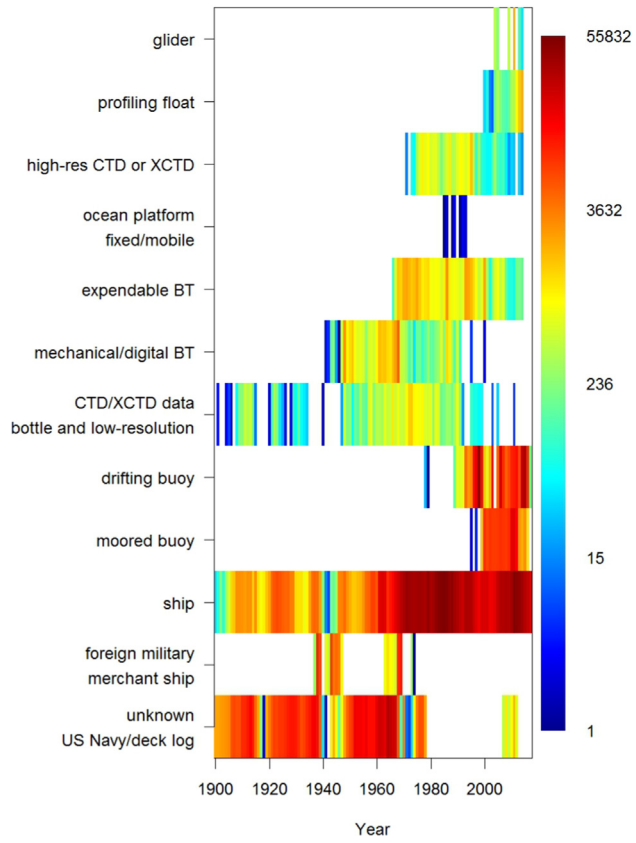

Fig. 2. Instruments for SST in situ measurements from 1800 in ICOADS.

of wood, canvas, tin, leather,brass, rubber, and plastic to collect water samples [9]. After the advent of steam ships in the late nineteenth century, it was routine to measure the temperature of the sea water that was circulated through the steam condenser. Most used instruments for SST measurements were condenser or engine room inlet. Values were often reported manually on ship logbooks. Since the 1970s, a growing number of ships have been equipped with dedicated sensors either outside or inside the hull. These have been joined by a growing array of moored and drifting buoys which make automated measurements that are relayed by satellite. At present, around 90% of all SST observations come from buoys [9]. The majority of moored buoys measure SST at a nominal depth of 1 m. The largest systematic errors are found in the firsts decades since 1940s, when SST measurements were mostly made using buckets and room inlet [11]. Buckets allow to measure the temperature of the surface layers of the sea. These measure can be affected by large systematic errors due to the combined actions of latent and sensible heat transfer and the warmth of the sun. Moreover the human factor could affect the sampling and reporting accuracy. Improvements in bucket design in order to reduce the physical effects of boundary conditions and economical advantage

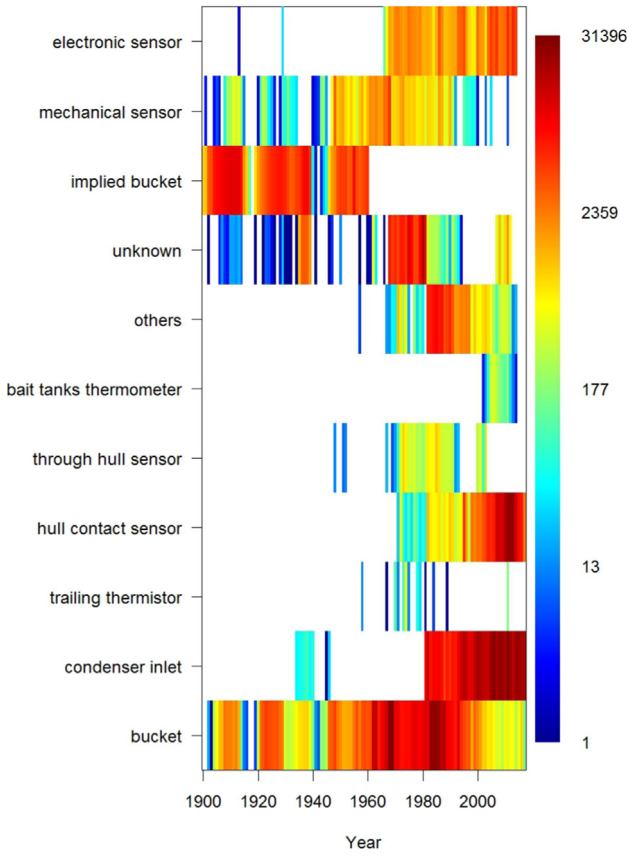

Fig. 3. Sensor for SST in situ measurements from 1800 in ICOADS.

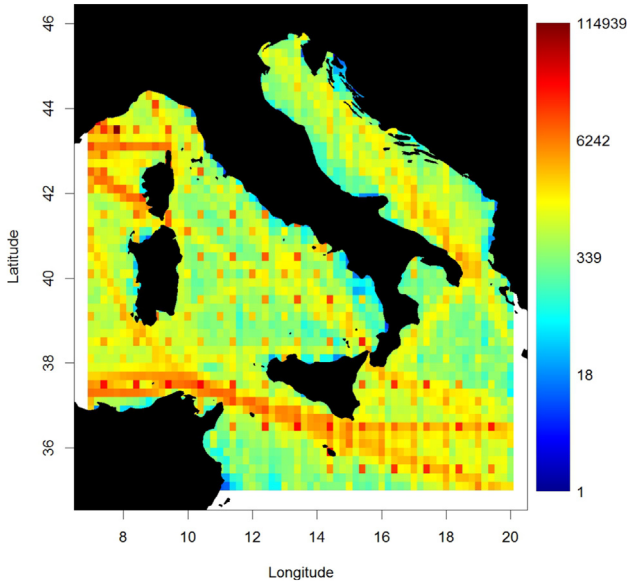

Fig. 4. Spatial frequency distribution of SST observations from 1900 in ICOADS for Italian Seas.

let this system to be already used even if larger and faster modern ships could affect the related measures. Room inlet systems measure at depth greater than 1 meter, depending on the ship, and are systematically affected by the same kind of bias due to the influence of internal engine temperature. The development of new kind of sensors (Fig. 3) such as electronic thermistors improves the quality of measures and are at the present largely used in combination with moored and drifting platforms or ship hulls.

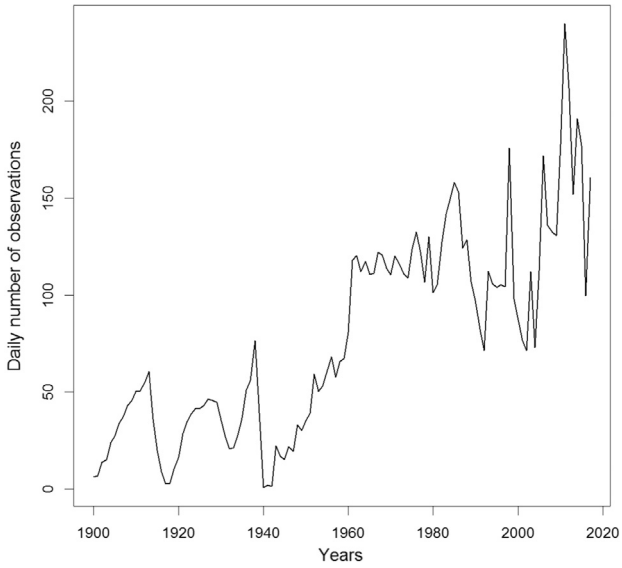

Fig. 5. Number of SST observations per day from 1900 in ICOADS for Italian Seas.

The great effort made to homogenise and collect almost all the existing in situ measurements in digital archives allowed to reconstruct the longest SST series worldwide. The latest release of ICOADS (3.0), contains individual marine reports from 1662 up to now but due to sparse and few observations untill the beginning of the twentieth century, only data from 1900 are taken into account. These observations are heterogeneous because over these years the spatial and temporal coverage is variable (see Figs. 4 and 5), in some case extremely poor, corresponding to the first years of 1900 and during the world wars.

This critical point introduces a bias in long-term analysis that could strongly contaminate the trend analyses [12]. Several works have been implemented in order to homogenise data and detect systematic errors in SST measurements ([3,13,14]). The last releases of ICOADS (3.0) introduce quality control procedures that take into account some of these corrections [10]. In particular, ICOADS products return monthly means of SST observations over 2° latitude x 2° longitude boxes since 1900 (ICOADS 2 Degree). Due the heterogeneity of information sources, the evaluation of measurements accuracy is not provided. Nevertheless, several studies implemented by Kennedy et al. [3,4,9] try to consider the various components that contribute to the overall uncertainty by using statistical models for systematic and random errors. Following the use of modern techniques of observation and an increasing number of fixed and drifting platforms, a second ICOADS product, ICOADS 1 Degree, gathering monthly means SST values computed over 1° latitude x 1° longitude boxes since 1960, is characterised by complete and almost correct information as during these years data are relatively dense and homogeneous. The increased spatial resolution allows to describe the complexity of semi-enclosed basins typical of the Italian Seas, which physical conditions are influenced by the orography of the coast. Although this improvement, the measurements along the coastal areas are still affected by a poor accuracy essentially due to the limited number of installed measurement stations. For both datasets, quality controls (QC) consisting in trimming procedures based on standard deviation limits have been implemented by ICOADS group [15,16], by incorporating large time and space climate signals (e.g., El Niño and La Niña) into standard and adaptive QC. However, the product is still considered experimental.

2. In ISPRA (Italian Institute for the Environmental Protection and Research) systematic in situ SST measurements started from the mid-nineties, with the upgrading of marine monitoring networks already collecting several meteorological and physical parameters along the Italian coasts.

   The Italian tide-gauge monitoring network (Rete Mareografica Nazionale – RMN, [17]) is composed by 36 measuring stations mainly located in the harbours. The sea temperature is measured through a sensor located into the stilling well.
3. The Italian data buoy network (Rete Ondametrica Nazionale – RON, [18]) consists of 15 instruments in open sea. Buoys are moored approximately at the 100 m bathymetry and the gauge is positioned below the hull. In both cases sensors are located about 1.0 m under the sea level in calm conditions and this particular protected position avoids the effects of the sun radiations.

   During the last years, both networks continuously collected SST data every 30 min, measuring through a platinum resistance thermistor (RMN) with a sensitivity of 0.03 °C and an accuracy of ± 0.1 °C and a composite thermilinear component (RON) that consists of a thermistor and a resistor set with an accuracy of ± 0.15 °C. Standard quality control procedures according to main international guidelines [19] and advanced statistical models [20–22] have been applied to reduce outliers and gaps. Periodic maintenance activity and further comparison with related dataset have been performed in order to avoid errors related to malfunctioning temperature thermistors, interferences on transmission, uncalibrated sensors or position misalignment in station position.
4. The development of satellite and remote sensing systems allows to improve the spatial resolution of SST observations. However, without reference to in situ measurements most satellite-based SST products will contain large-scale biases due to varying atmospheric composition and imperfect instrumental calibration [12]. In the framework of Copernicus program, the CNR MED Sea Surface Temperature provides SST values over the Mediterranean Sea [23]. The data are obtained from night-time images acquired by the infrared sensors flying on both geostationary and polar orbit satellites through sensors like the Advanced Along Track Scanning Radiometer (AATSR, ENVISAT), MODerate resolution Imaging Spectroradiometer (MODIS, on both Aqua and Terra satellites), Advanced Very High Resolution Radiometer (AVHRR, on METOP satellite and NOAA satellites), Spinning Enhanced Visible and Infrared Imager (SEVIRI, Meteosat Second Generation) with different spatial and temporal resolution. The sea surface emits radiation in the infrared and the microwave wavelengths. Satellite sensors can measure these bands whose amplitude varies with temperature. Infrared radiation of the ocean comes from the top 10 microns of the surface while microwave radiation results from the top 1 mm layer. Infrared satellite sensors have better spatial resolution but are more susceptible to cloud contamination than microwave. This is due to the absorption of the ocean emitted infrared energy by clouds. Microwave instruments measure an approximation to the SST subskin in any weather conditions, thus have fuller coverage but at a reduced spatial resolution [24]. Furthermore SST measurements can be significantly distorted by outliers in case of anomalous atmospheric conditions and high SST gradient areas (e.g., at the boundaries of oceanic currents or upwellings). This amount of observed information and integrated quality control procedures generates daily gap-free maps (L4) at 0.0625 degrees resolution though statistical interpolation methods. The Mediterranean L4 operational products have then been validated using in situ SST measurements from drifting buoys, covering two years of data (2010–2011). This dataset represents the state of art and probably it is the best calibrated and validated SST dataset available. The Group for High Resolution SST (GHRSST) implemented specific algorithms to monitor the quality of SST from satellites and analysed L4 products with respect to SST field reference standard [25,26].

3. Materials and methods

Taking into account the bias sources related to the four datasets, spatial and temporal statistics have been evaluated. It is well known that averaged values allow to reduce the effects of random errors that could affect the single observation. The reconstructed time series have been restricted in a temporal domain from 1900 to 2016 and in a spatial domain corresponding to Italian Seas (latitude $35°N-46°N$, longitude $7°E-20°E$).

3.1. Long-term SST series

The ICOADS 2 Degree monthly mean SST dataset cover a temporal domain of about 120 years. In the selected period, the dataset counts 2.5% of missing values gathered in small gaps during the world wars (1917–1918 and 1940–1943). The poor spatial resolution allows to represent the geographical domain with a limited number of points on a regular grid, from a minimum of 20 (first decade of 1900) to 34. Since the illustrated restrictions of this dataset, only a qualitative evaluation of standard thirty-year periods (1900–1929; 1930–1959; 1960–1989) in Tyrrhenian Sea has been performed. A non parametric kernel density estimation has been computed for each period in terms of deviation from the mean SST value in 1960–1989. As comparative result, the monthly deviation of the 2016 has been reported.

The ICOADS 1 Degree monthly mean SST dataset starts in 1960. In the selected period, the dataset has no missing values and the increased spatial resolution allows to represent the geographical domain with 98 grid points. The temporal trend of the Tyrrhenian and Adriatic SST monthly mean series has been analysed by fitting a local polynomial regression and its confidence interval, in order to evaluate the temperature variability over the years respect to the mean level. The model fitting have been performed through the ggplot package in R-CRAN software that perform as smooth function the loess algorithm [27,28].

3.2. Short-term SST series

RMN tide gauges SST data involved in the analysis start from 2000 up to 2014. Respect to the ICOADS datasets, this kind of data could reproduce the local SST variability describing the temperature dynamics along the coast. Furthermore, the analysis of time series obtained from measurement stations belonging to the same sea helps to detect typical basin regimes over the years. Five RMN station in Tyrrhenian Sea have been exploited in terms of annual means in order to individuate the local and general behaviour of the basin. Statistical parameters have been computed only if yearly missing data percentage is less than 20% to avoid seasonal effects.

CNR-MED SST data are available from 2008 up to 2016. This set of data is very useful to identify spatial and temporal dynamics at different scales (local, regional, basins, seasonal, annual, etc.) with daily values over more than 1,200,000 grid points in the geographical domain. At the moment, the limited temporal span affects a long term analysis of these series. However, in the future, it could represent the target for long term studies.

The spatial distribution of the mean SST in the period 2008–2015 provides the climatology for the Italian Seas. Anomaly of the mean SST value in 2016 with respect to the previous periods (2008–2015) are calculated to investigate local phenomena that could generate great differences in temperature regimes in a limited period. On the other hand, maps of frequencies of moving window minimum and maximum SST values have been reported. These plots are useful to show areas mainly exposed to extreme values.

3.3. Comparison of SST time series

The comparison of presented long-term and short-term SST series is affected by a number of limitations, in particular:

- the different spatial resolutions: all spatial datasets have different resolution and the extraction of collocated data (in situ data versus regular grids and vice versa) could introduce great bias;
- local effects when comparing SST values along shoreline due to morphological and orographic characteristics;
- the different temporal domain: in particular the most informative dataset (CNR MED) is limited a few years of measures and this limits a comparison with long-term ICOADS datasets;
- the well known limitations of ICOADS measurements already described.

The limitation of the comparison along the coasts is evident from the joint analysis of RMN and CNR-MED datasets. As an example of this restriction, distribution of residuals between SST values at Napoli, Palinuro and Palermo measurement stations (RMN) and the corresponding data extracted from CNR-MED dataset have been calculated and compared.

To perform a valuable comparison, only two datasets (ICOADS 1 Degree and CNR-MED) have been selected starting from 2008. The different spatial resolution of the data sources has been taken into account by computing the overall monthly mean values for the Tyrrhenian and the Adriatic Sea for both datasets, obtaining two univariate time series for each region. Boxplots of residuals between ICOADS and CNR-MED sets have been drawn to highlight the different temperature distributions in the two basins. Moreover the linear regression of the residuals versus the seasonal variability has been performed. To define the seasonal component, three variables have been introduced:

- Cold season (December, January, February, March);
- Warm season (June, July, August, September);
- Mild season (April, May, October, November).

The estimated coefficients, while statistically significant, have been used to correct the time series and trends. This preliminary analysis should be upgraded with longer time series.

4. Results

4.1. Long-term SST series

Thirty-year period distributions of deviation from the monthly mean SST in 1960–1989 have been reported in Fig. 6. The first order peaks distances suggest that the differences between the first period (1900–1929) and the others two are relevant, especially from August to January when the distance between mode distributions is about + 1 °C. The distance between monthly mean values in 2016 and the past years is more significant with higher differences in winter (+ 1.4 °C from referring level) and minimum differences in summer.

SST Trend in Tyrrhenian Sea is shown in Fig. 7. Respect to the whole average SST (about 19 °C), there is a cooling of 0.5 °C in 1970–1990, while a warming of 0.9 °C during the last 10 years.

4.2. Short-term SST series

Annual means differences of Sea Surface Temperature in the period 2001–2014 respect to mean SST in 2000 are computed at five RMN stations (Civitavecchia, Napoli, Palinuro, Palermo, Cagliari), and reported in Fig. 8. These histograms shows a non stationary phenomena with a large interannual variability, typical of coastal area that are affected by local circulation and land contamination, without a clearly trend. This behaviour is emphasised for stations influenced by warm and cold circulations coming from the western Mediterranean sea. For all the five gauges, the period 2011–2014 is the warmest, with maximum in 2014 (+ 0.7 °C respect to SST in 2000).

Fig. 9 shows the SST climatology as the average spatial distribution

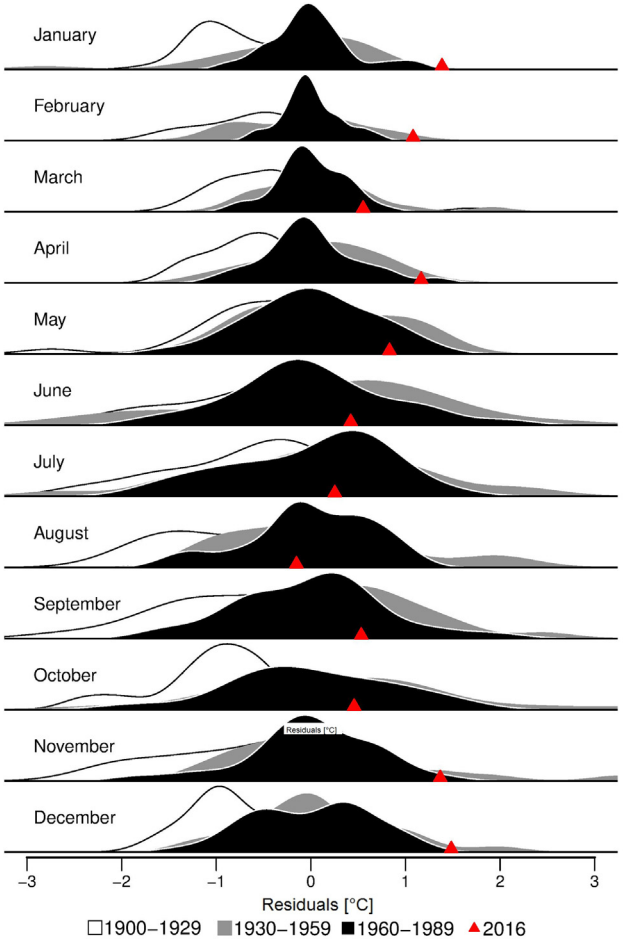

Fig. 6. Density distributions of thirty-year periods monthly means SST deviation in Tyrrhenian Sea. Red dots refer to the deviation of monthly means of 2016 (ICOADS 2 Degree dataset).

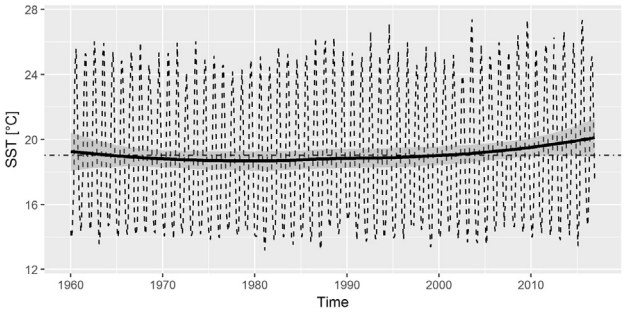

Fig. 7. Trend fitting (solid line) in Tyrrhenian Sea through local polinomial regression. The monthly SST time series in dashed line while the dot-dashed line represent the global average value (ICOADS 1 Degree dataset).

of SST in 2008–2015 and Fig. 10 the anomaly field in 2016 with respect to same period and it is computed as the differences between annual SST mean in 2016 and the average over the 2008–2015. The total anomaly is + 0.14 °C with warmest areas around the western Mediterranean sea, the Ionian Sea and the Strait of Bonifacio.

Using a spatial moving window of 1 × 1 degrees, distributions of maximum and minimum are reported in Figs. 11 and 12. Maximum in Fig. 11 are mainly concentrated in particular areas along the coasts and in the central Tyrrhenian and Ionian Sea. Similarly, minimum SST values in Fig. 12 are located along shore in correspondence of the major river mouths, and distributed along a passageway between Strait of Messina and Strait of Bonifacio.

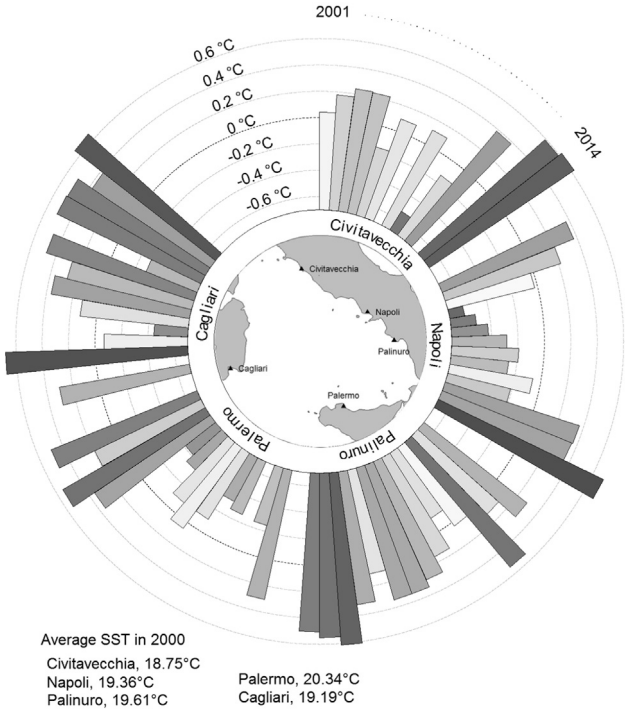

Fig. 8. SST Annual means distributions in Tyrrhenian Sea from RMN observations with respect to average SST value in 2000 for each measurement station. Darker bar identifies periods with highest anomalies respect to the referring level (RMN dataset).

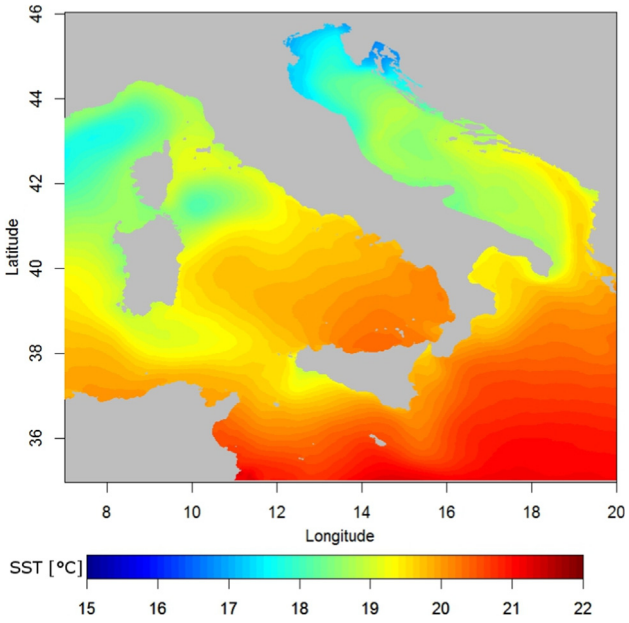

Fig. 9. SST spatial distribution (climatology) in 2008–2015 (CNR-MED dataset).

4.3. Comparison of SST time series

In order to verify the differences between RMN and CNR-MED data in coastal areas, residuals of SST values at Napoli, Palinuro and Palermo tide gauges and corresponding time series in closest cells of CNR-MED dataset are computed. The empirical distributions of these residuals (Fig. 13) reflect the influence of complex orographic conditions, as gulfs, or anthropic pressures that generate positive differences in Palermo and negative differences in Napoli, while in case of open sea

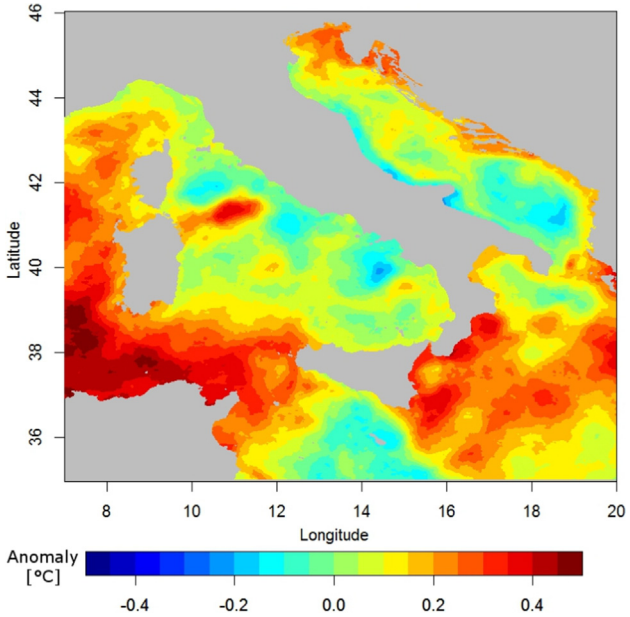

Fig. 10. SST spatial anomaly in 2016 with respect to SST climatology in 2008–2015 (CNR-MED dataset).

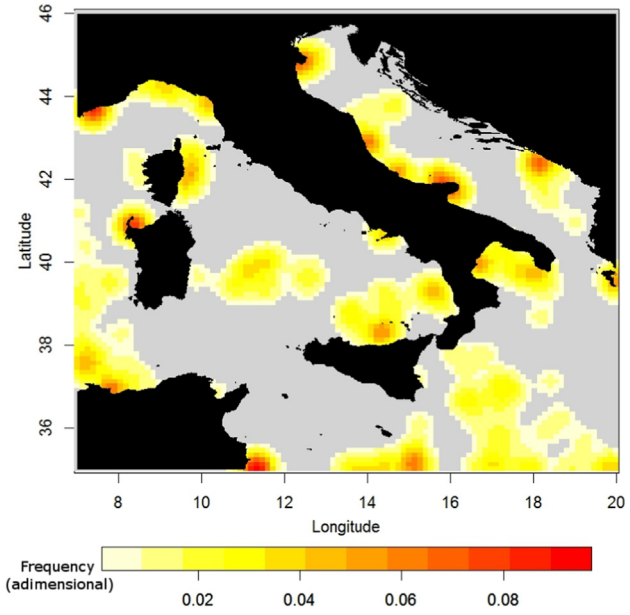

Fig. 11. Frequency distribution of moving window maximum of SST (CNR-MED dataset).

exposure, as in Palinuro, the correspondence between SST series is higher (bias close to 0).

Fig. 14 describes the monthly time series in the Adriatic Sea, where the ICOADS dataset tends to overestimate colder temperatures and underestimate warmer ones. Fig. 15 shows the scatterplot of the overall monthly mean SST from ICOADS and CNR-MED datasets where an estimated linear model between variables (intercept and slope significantly different from 0 and 1) confirms the behaviour. Despite the bias related to the use of different sources of data, the time series of overall monthly mean SST from ICOADS 1 Degree dataset and corresponding series from CNR-MED dataset present a good agreement for Tyrrhenian and Adriatic Sea. Nevertheless some evidence in the time series plots suggests the need of introduce the analysis in terms of seasonal component.

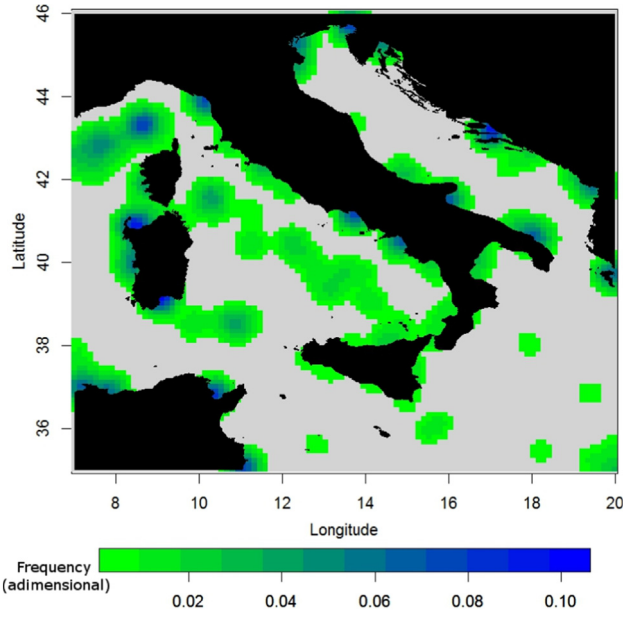

Fig. 12. Frequency distribution of moving window minimum of SST (CNR-MED dataset).

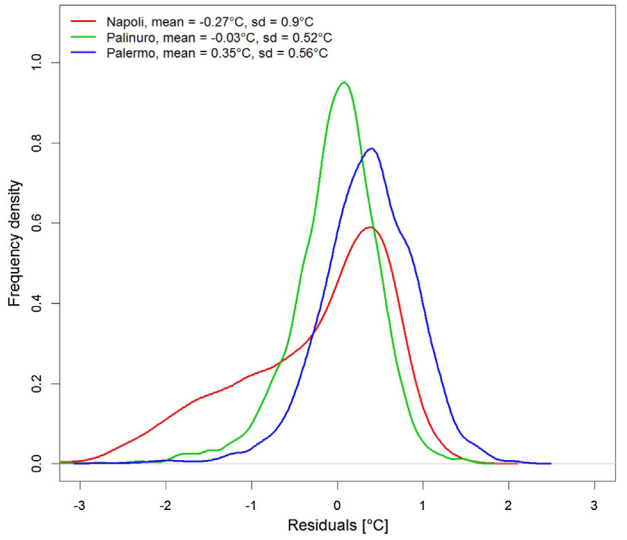

Fig. 13. Empirical distributions of residuals between RMN and CNR-MED data.

Annual boxplots of overall monthly mean SST residuals between the two analysed time series (Fig. 16) allow to describe different regimes in Adriatic and Tyrrhenian Sea. While in the Tyrrhenian Sea residuals are more homogeneous with medians positive but close to zero, on the other hand, in Adriatic Sea the same values are spread with positive and higher median than in the Tyrrhenian Sea.

Table 1 reports the coefficient estimates of the following linear regression model:

$$SST_{ICOADS} - SST_{CNR-MED} = C_{Cold}\delta_{Cold} + C_{Warm}\delta_{Warm} + C_{Mild}\delta_{Mild} + \varepsilon$$

in this model residuals are the predictors and seasons are regressors; moreover δ_X is equal to 1 if the corresponding residual value belongs to season X, 0 otherwise and C_X is the coefficient related to season X. This relation has been used to process the whole time series since 1960 in order to calibrate the trend analysis already presented in Fig. 7 by introducing a seasonal correction factor suggested by the evaluated model. All estimates are highly significant, except to the warm season in Adriatic Sea and are positive in cold and mild seasons while negative

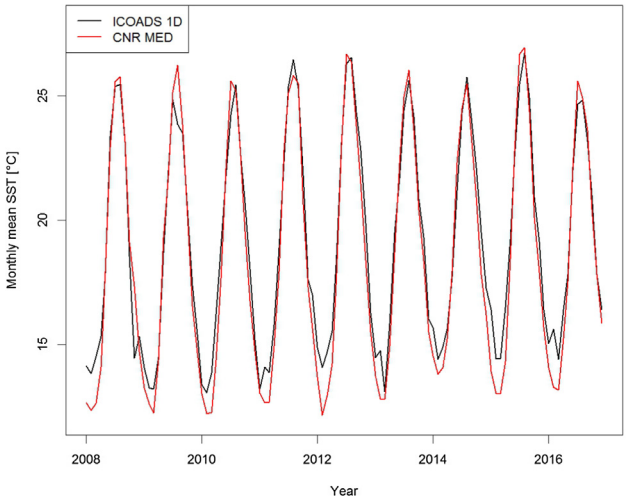

Fig. 14. Comparison between ICOADS 1D and CNR-MED monthly mean SST in Adriatic Sea).

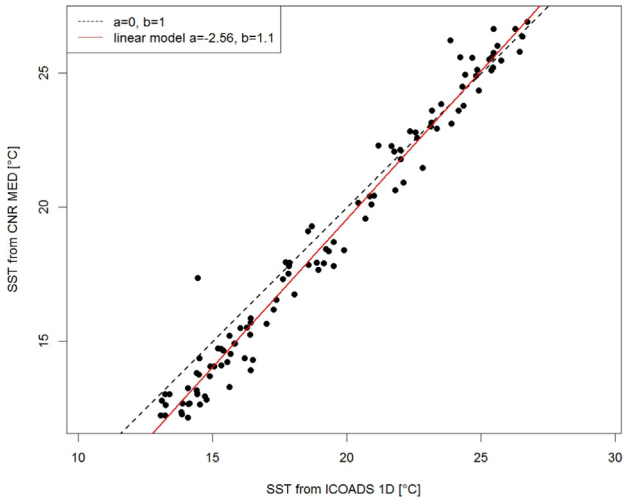

Fig. 15. Scatterplot of the overall monthly mean SST from ICOADS and CNR-MED, with estimated linear model (solid red line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

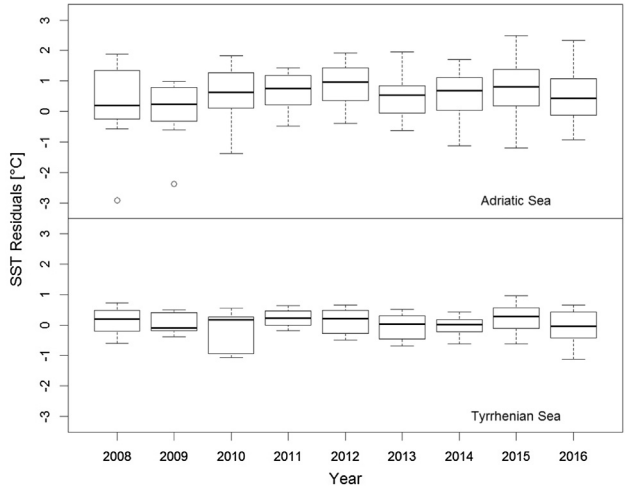

Fig. 16. Annual boxplots of monthly mean SST residuals (ICOADS 1 Degree – CNR-MED datasets)).

Table 1
Coefficient estimates of linear model between residuals ($SST_{ICOADS} - SST_{CNR-MED}$) vs seasons.

Season	Estimate	Std. Error	Sig. Level
	Tyrrhenian Sea		
Cold	0.25824	0.06372	<0.001
Warm	−0.31482	0.06372	<0.001
Mild	0.17424	0.06372	0.01–0.001
	Adriatic Sea		
Cold	1.1079	0.1183	<0.001
Warm	−0.2108	0.1183	0.05–0.1
Mild	0.6997	0.1183	<0.001

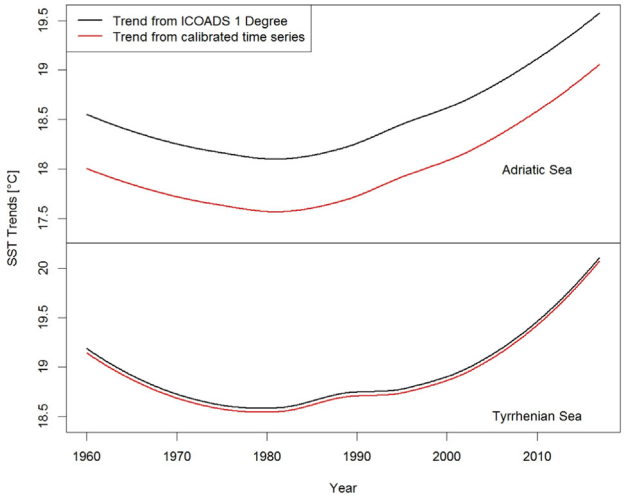

Fig. 17. Trends from ICOADS 1 Degree (black) and calibrated SST time series (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the warm one. In particular in the Tyrrhenian Sea, estimated coefficients are lower, confirming a good agreement between the two datasets in open seas. On the other hand, higher coefficients in Adriatic estimates suggest the difficulty in ICOADS dataset to represent the variability of SST in semi enclosed basins. In Fig. 17 the trend analysis has been corrected taking into account the model estimates. While the correction in Tyrrhenian Sea is minimal, in the Adriatic Sea it is more relevant and approximately of $0.5°C$.

5. Conclusions

The study aims to use multiple data source, with different spatial and temporal resolution, in order to describe significant SST regimes in Italian Seas. Comparison limitations in coastal areas have been discussed and a deeper effort is needed in order to improve data quality. On the other hand, at the basin scale, the SST series present a good agreement, despite the different characteristics of dataset involved and the limits highlighted.

As expected, a better agreement is evident in Tyrrhenian Sea due to the homogeneous hydrographical conditions typical of the open sea basins, while the heterogeneity in the Adriatic Sea reflects the complexity of local dynamics in semi-enclosed basins related to the orography and the freshwater inputs.

More work is required to extend results to all Italian Seas and to confirm evidences. It is fundamental to carry on with a rigorous SST monitoring in the following years from multiple sources in order to perform a good calibration of the past decades and to obtain correct trend estimation.

In this sense, RMN data could represent an additional source of information in order to asses the uncertainty on SST measurements.

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